4 Survey Datums

Today's multi-organizational Project Development efforts require the use of common, accurate horizontal and vertical survey datums and consistent, precise control-survey procedures to ensure the accurate location of fixed works and rights of way. These requirements are compounded by the expanding use of geographic information systems (GIS) by Caltrans, and other agencies. Universally accepted and used common survey datums are essential for the efficient sharing of both engineering and GIS data with Caltrans partners in developing and operating a multimodal transportation system.

4.1 Horizontal Datum

4.1-1 Policy

All engineering work (mapping, planning, design, right-of-way engineering and construction) for each specific Caltrans-involved transportation improvement project shall be based on a common horizontal datum.

The horizontal datum for all mapping, planning, design, right of way engineering, and construction on Caltrans-involved transportation improvement projects, including special funded State highway projects, shall be the North American Datum of 1983 (NAD83), as defined by the National Geodetic Survey (NGS). The physical (on-the-ground survey station) reference network for the NAD83 datum for all Caltrans-involved transportation improvement projects shall be the California High Precision Geodetic Network (CA-HPGN) and its densification stations (CA-HPGN-D).

As resources are available, Caltrans will, in cooperation with NGS and others, monitor and maintain the integrity of the CA-HPGN/HPGN-D:

- The ESC Geometronics Branch will coordinate Caltrans involvement in replacement of destroyed and disturbed HPGN/HPGN-D monuments and resurveys of the network in areas of significant seismic events.
- The Districts are to report disturbed or destroyed HPGN/HPGN-D monuments to the Geometronics Branch. In addition, the Districts should attempt to visit each HPGN/HPGN-D station once a year and transmit a report to the Geometronics Branch which describes the station, its status and any changes in the "to reach" description. Changes in the "to reach" description are to be submitted in a format acceptable to NGS (currently, DDPROC). The Geometronics Branch will consolidate the data and forward it to NGS.

As resources permit, the CA-HPGN shall be densified within the corridor areas of planned Caltrans-involved transportation projects prior to, or during, the project studies (planning) phase to provide consistent, convenient geodetic reference monuments for all subsequent project-related surveys. The densification surveys shall be performed in accordance with the policies, standards and procedures described in Section 9, "Corridor Control Surveys."

4.1-2 Description of NAD83

The sea-level surface of the Earth is called the geoid and is defined as the surface that is perpendicular to the direction of gravity at all points. The geoid is not a mathematically definable geometric shape. It is irregular because the direction of gravity varies from point to point as the result of the irregular distribution of mass within the earth.

Because of its irregular non-mathematical shape, the geoid cannot be used for calculations of the relative horizontal positions of points on the earth's surface. So, a representative geometric surface that approximates the geoid is used to perform positional calculations. The reference surface used for the North American Datum of 1983 (NAD83) is an ellipsoid named the Geodetic Reference System of 1980 (GRS80). GRS80, is a world-wide model which has replaced the previously-used Clarke's spheroid of 1866. Clarke's Spheroid, the reference figure for NAD27, was a best-fitting model for North America, but did not meet the needs of world-wide geodetic systems or the Global Positioning System (GPS).

NAD83 was established by first performing a least squares adjustment of all the observations used to establish the NAD27 network and then redefining the mathematical reference surface from Clarke's Spheroid to the GRS80. NAD83 has geodetic coordinates that measure 70 to 100 m different from those of NAD27. There is no direct mathematical method to accurately transform coordinates from one system to the other. Data conversion programs such as NADCON, developed by NGS, and CORDSCON, developed by the Army Corps of Engineers, are only approximations that are not accurate enough for boundary or engineering surveys. With a general accuracy of 0.15 m these programs are satisfactory for some map conversions.

The geodetic coordinate system for NAD 83 is based on longitude defined as angular distance East or West of the prime meridian which runs through the observatory at Greenwich, England, and latitude defined as the angular distance North or South of the Equator.

4.1-3 NAD83 Epochs

The initial NGS station coordinates based on NAD83 were the result of a simultaneous nationwide adjustment of the original observation that incrementally built up the NAD27 network. The adjustment results were published in 1986. Subsequently, in 1991, the CA-HPGN was established using GPS technology. The GPS survey was more precise than the methods used to establish the NAD83 reference system in 1986. Consequently, coordinates for stations determined with reference to the CA-HPGN are more accurate and may differ from those referenced to the original NAD83 positions as much as one meter. To avoid confusion, an epoch (date) must be designated for all NAD83 data.

Much of California is affected by relatively large crustal motions, both secular (constant slip) and episodic (earthquake). Secular crustal motions can exceed 0.04 m per year are observable with GPS surveys. Already (October 1995) portions of the CA-HPGN have been resurveyed because of the Landers, Northridge, and Mendocino earthquakes. These resurveys will continue to be necessary to maintain the accuracy of the CA-HPGN as the crustal motion constantly works to degrade the network. Each CA-HPGN resurvey is labeled with an epoch and all surveys using CA-HPGN for control must note the applicable epoch. The epoch of the original CA-HPGN survey is 1991.35. This is a dating system which indicates the mean date that the survey was conducted. The numbers to the right of the decimal point are derived from the day of the year. In this case, multiply 0.35 times 365 days to find that the mean date of the original CA-HPGN survey took place on the 128th day of the year or May 8, 1991.

Surveys with different epochs can be related by using the NGS Horizontal Time Dependent Positioning (HTDP) computer program. The program translates geodetic data from one epoch to another based on a model for secular crustal motions. New versions of HDTP also account for episodic motion. Using HTDP, surveys can be planned using control stations with coordinates from different epochs. For instance the program will adjust the NAD83 (1991.35) coordinates for a control station to NAD83 (1992.88), so it can be used with other control having NAD83 (1992.88) coordinates. HTDP eliminates most of the systematic error introduced by crustal motion and ensures accuracies within about 0.02 m.

4.2 Vertical Datum

4.2-1 Policy

The vertical datum for all mapping, planning, design, right of way engineering, and construction on Caltrans-involved transportation improvement projects, including special-funded State highway projects shall be the North American Vertical Datum of 1988 (NAVD88), as defined by the National Geodetic Survey (NGS). Exceptions to this policy, as determined by the District Survey Engineer in consultation with the Project Manager are permitted for:

- Projects that are small, remote and isolated.
- Maintenance, traffic safety and rehabilitation projects that are controlled by existing fixed works.
- Projects for which it is not cost effective to establish NAVD88 vertical control.
- Expedited projects for which it is not feasible to establish NAVD88 vertical control.
- Projects contiguous to the National Geodetic Vertical Datum of 1929 (NGVD29) projects and uniformity is desirable.

Generally, the only acceptable alternate datum is NGVD29. For project locations where published NAVD88 data is not locally available, GPS survey methods using GEOID93 or future geoid models of improved resolution should be considered. The standard deviation for results obtained from GEOID93 over a distance of 100 km is 0.1 m. Assumed datums should only be considered as a last resort.

All engineering work (mapping, planning, design, right-fo-way engineering and construction) for each Caltrans-involved transportation improvement project shall be based on common vertical datum.

4.2-2 Description of NAVD 88

In 1978, NGS began a program to combine leveling surveys into a single least squares adjustment to provide improved heights for over 700,000 vertical control points throughout the United States. This adjustment was completed in June, 1991 and has been designated the North American Vertical Datum of 1988 (NAVD88). NGS selected the GRS80 Ellipsoid at a single station as the minimum-constraint datum point for NAVD88.

Approximately 80 percent of all NGS first-order and second-order benchmarks were incorporated into the nationwide adjustment. But, in California only about 25 percent of the benchmarks were included. The presence of subsidence and crustal motion has precluded the inclusion of the remainder of the vertical control stations into NAVD88 without extensive additional leveling surveys. The United States Geological Survey (USGS), Corps of Engineers, and Caltrans vertical control has not been included in the NAVD88 adjustment. This greatly decreases the availability of NAVD88 published data compared to that for NGVD29 in California.

Published NGVD29 and NAVD88 elevations for benchmarks located in subsidence areas are accurate only at the epoch (date) for the published elevation. Local vertical control and mapping are generally based on the most recent published epoch elevation for the NGVD29 vertical datum even though it is known that subsidence has occurred. At many locations in California, subsidence exceeds ten feet, which makes many bench marks significantly in error when compared to the national network datum. With NAVD88, this situation will continue to exist but will be exacerbated by the minimum number of published NAVD88 elevations in subsidence areas.

4.2-3 GPS Determined Heights

GPS survey methods, besides enabling the horizontal positioning of survey points to a high degree of accuracy, also provide accurate ellipsoidal height information. Whereas, all geodetic leveling is relative to a height or elevation (orthometric height) above the geoid, GPS heights are determined in relation to the GRS80 ellipsoid. The difference between the geoid (an irregular surface defined by variations in the earth's gravity field) and the ellipsoid (a mathematical surface) is referred to as geoid height. The relationship between the geoid, GRS80 and the earth's surface is shown in Figure 4-1 and is given by Equation 4-1.

Equation 4-1:

$$h = N + H$$

where:

h = ellipsoidal height
N = geoid height
H = orthometric height (elevation)

In California geoid heights are all negative, indicating the geoid is below the ellipsoid as shown in Figure 4-1. Geoid93, a model of geoid heights is now available from NGS and is being used extensively in GPS data reduction to obtain elevations.

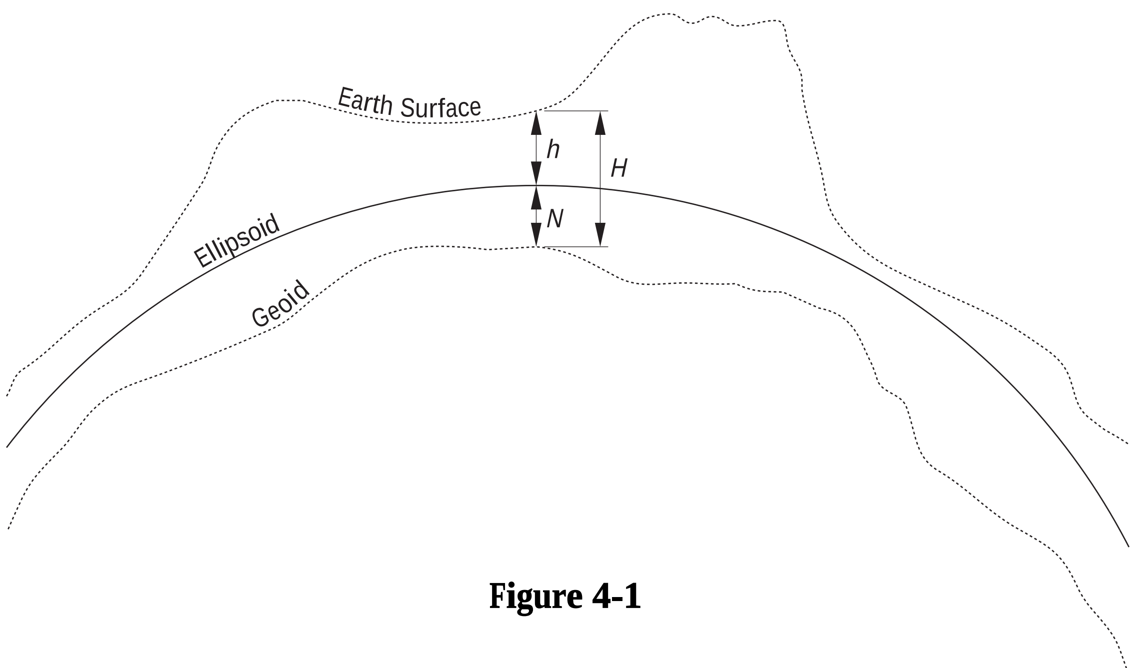


Figure 4-1

4.2-4 Datum Conversions

NGS and other public agencies that maintain bench marks periodically readjust level networks as new field data is obtained. Care should be taken to always use elevations from the most recent adjustment. When using the published elevations and bench marks of other agencies, it is important to convert them to the datum selected for the Caltrans project.

Because NAVD88 is an independent readjustment and redefinition of NGVD29 there is not a precise mathematical method to convert exactly between the two datums. If using a conversion program like NGS's VERTCON to convert NGVD29 elevations to NAVD88, be sure to verify that the results will meet the accuracy requirements of the work to be performed. Generally, accuracies when using VERTCON are within 0.25 m.

4.3 The California Coordinate System

4.3-1 Policy

Section 8817 of the *Public Resources Code* requires that all new surveys and new mapping projects, which use State Plane Coordinates, must use the California Coordinate System of 1983 (CCS83). CCS83 is based on NAD83.

CCS83 is the coordinate system used for all mapping, planning, design, right-of-way engineering, and construction on Caltrans-involved transportation improvement projects including special-funded State highway projects. The physical (on-the-ground) reference network for CCS83 is the CA-HPGN.

Coordinates shown on maps, plans, and other related documents shall be CCS83 coordinates. The reference network for CCS83 coordinates shall be the CA-HPGN.

When a map, set of plans, or other document uses State Plane Coordinates, a note shall be placed on the document to show the basis of the coordinates used including: the CCS zone, and the physical reference network, and epoch used to establish the coordinates (see Section 4.1-3, "NAD83 Epochs").

4.3-2 Description of CCS83

Because of the complexity of performing the calculations for geodetic surveying and the limited extent of most surveying projects, most surveyors generally use plane surveying methods. For local projects, plane surveying yields accurate results, but for large systems like the Caltrans transportation system local plane surveying systems are not adequate. Not only are local plane coordinate systems inaccurate over large areas, but they cannot be easily related to other local systems.

In response to the needs of local surveyors for an accurate plane surveying datum useful over relatively large areas, the U. S. Coast and Geodetic Survey (the predecessor of NGS) developed the State Plane Coordinate Systems. The first system for California (CCS27) was based on NAD27. CCS83 was later established to utilize the more precise NAD83 datum.

The State Plane Coordinate System was established to provide a means for transferring the geodetic positions of monumented points to plane coordinates that would permit the use of these monuments in plane surveying over relatively large areas without introducing significant error.

A plane-rectangular coordinate system is by definition a flat surface. Geodetic positions on the curved surface of the earth must be “projected” to their corresponding plane coordinate positions. Projecting the curved surface onto a plane requires some form of deformation. Imagine the stretching and tearing necessary to flatten a piece of orange peel. In California the Lambert Conformal map projection is used to transform the geodetic positions of latitude and longitude into the *y* (Northing) and *x* (Easting) coordinates of the CCS83.

The Lambert Conformal projection can be illustrated by a cone that intersects the GRS 80 ellipsoid along two parallels of latitude as shown in Figure 4-2. These latitudes are known as the standard parallels for the projection. Distances lying along the standard parallels are the same on both the GRS80 ellipsoid and the cone. Between the standard parallels, distances projected from the ellipsoid to the conic surface become smaller. Outside the standard parallels, distances projected from the ellipsoid to the conic surface become larger. Scale factors are used to reduce and increase distances when converting between the CCS surface and the ellipsoid surface. The scale factor is exactly one on the standard parallels, greater than one outside them and less than one between them.

The limits of each Lambert projection are generally chosen so that scale factors will be less than 1.00010 and greater than 0.99990 so that even if scale factors are disregarded discrepancies between ground measurements at sea level and distances on the CCS grid will be within 1:10000. Maintaining the 1:10000 constraint requires six zones in California. The zones have been created so that zone boundaries run along County lines. See Figure 4-3.

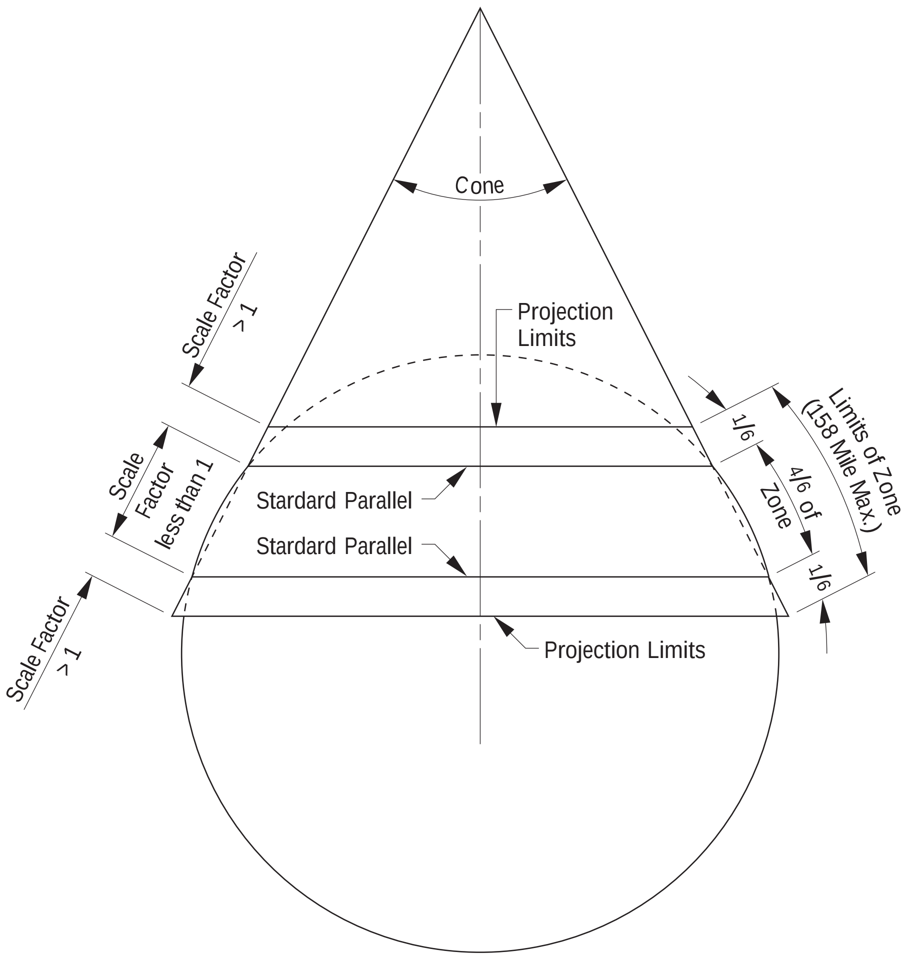

Cone
Projection Limits
Scale Factor > 1
Scale Factor less than 1
Stardard Parallel
Stardard Parallel
Scale Factor > 1
Projection Limits
1/6
4/6 of Zone
1/6
Limits of Zone (158 Mile Max.)

Figure 4-2

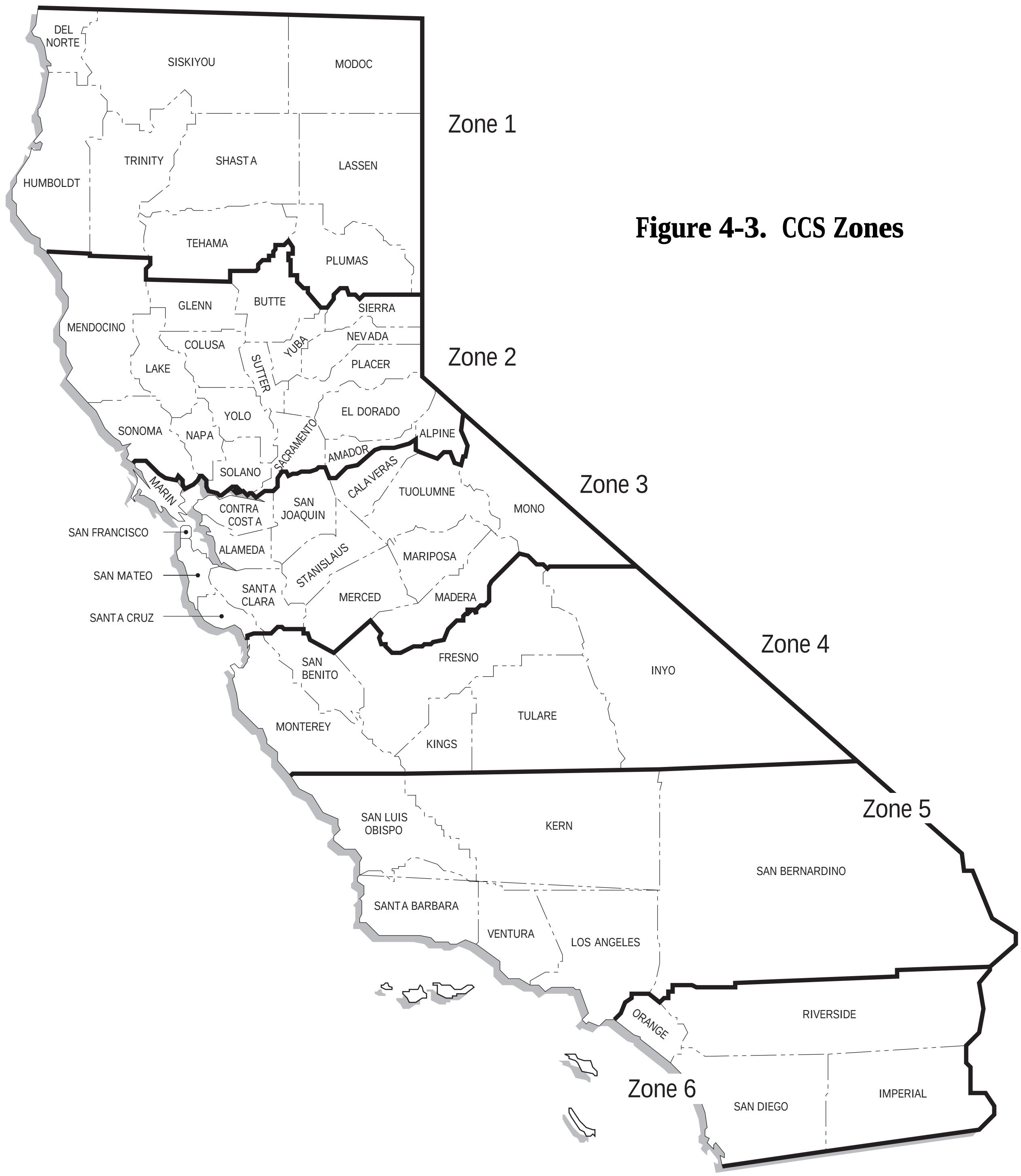
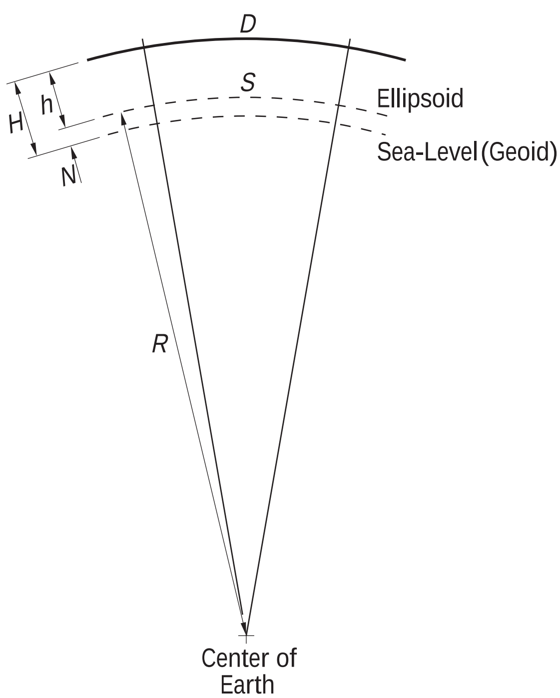


Figure 4-3. CCS Zones

Distances measured on the surface of the Earth must be scaled to corresponding lengths on the ellipsoid. This ellipsoidal or elevation factor varies with the elevation of the surface where the distance is measured. As the elevation of the measured line increases, the distance (radius) from the surface of the earth to its center increases, which correspondingly increases the length of the measured line. Thus, distances must be reduced in proportion to the change in radius between the ellipsoid and the radius of the Earth's surface where the measurement is made. See Figure 4-4.



$$\frac{S}{D} = \frac{R}{R + h}$$

$$S = D\left(\frac{R}{R + h}\right)$$

or:

$$S = D\left(\frac{R}{R + N + H}\right)$$

Where:

S = Distance on ellipsoid
D = Distance on ground
R = Radius of ellipsoid for zone
N = Geoidal height
H = Elevation
h = Ellipsoid height

Figure 4-4

Normally the elevation factor (in CCS27 called the sea level factor) and the scale factor are combined by multiplication into a grid or combined factor. Distances measured on the earth's surface are converted to CCS83 grid distances by multiplying by the grid factor. Grid distances are converted to ground distances by multiplying the grid distance by the reciprocal of the grid factor.

Lines running east and west on the CCS83 grid are parallels of latitude. A Central Meridian is designated for each CCS83 zone and all other meridional lines on the CCS83 grid are constructed parallel to it. Therefore the only true geodetic north-south line on a CCS83 grid is the Central Meridian. All other north-south lines vary from geodetic North by the plane convergence angle (γ). The plane convergence angle varies with longitude, increasing as the distance from the Central Meridian increases. See Figure 4-5.

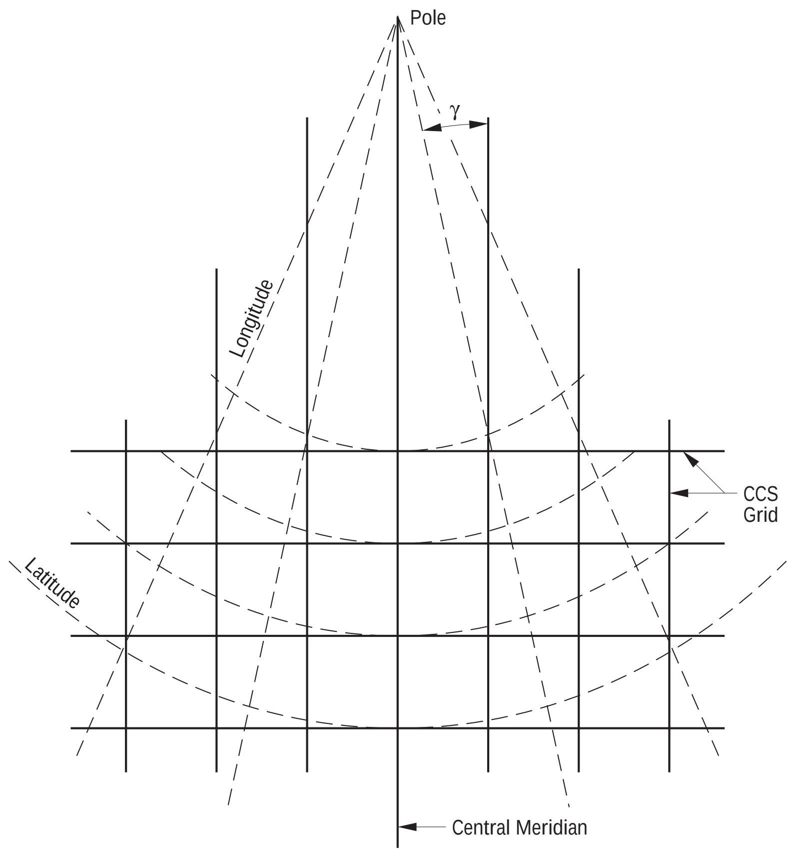


Figure 4-5

4.3-3 Coordinate Conversions

Conversions between geodetic coordinates and CCS83 coordinates are normally made using computer programs. The programs also calculate plane convergence angles and grid factors for each position. Though grid factors will differ from point to point because of change in elevation and latitude, as a general rule, a mean grid factor should be selected for each project. This policy will usually cause no appreciable loss in accuracy and will eliminate confusion caused by multiple grid factors. However for higher-order control surveys, where the elevations of points vary significantly, or for projects extending large north/south distances, assigning more than one grid factor may be appropriate.

CCS83 coordinates are specific for each zone because each CCS83 zone is a unique Lambert projection. Caltrans projects that extend from one zone into another should use CCS83 coordinates based only on one zone. CCS Coordinates for one zone can be easily converted to coordinates of a second zone by first converting to geodetic coordinates and then converting to CCS83 for the second zone.

There is no precise mathematical conversion for coordinates between CCS27 and CCS83. Conversion programs like the National Geodetic Survey's NADCON are only approximate conversions that are generally not accurate enough for engineering and boundary surveys. These programs should not be used to convert coordinates on survey control points between CCS27 and CCS83.

The two recommended methods for obtaining CCS83 coordinates for old CCS27 surveys are:

- Conducting a resurvey of the CCS27 survey using the CA-HPGN as the reference control.
- Use GPS to establish CCS83 coordinates on the original control points for the NAD27 survey and then recalculate coordinates for the entire network using the original observations.